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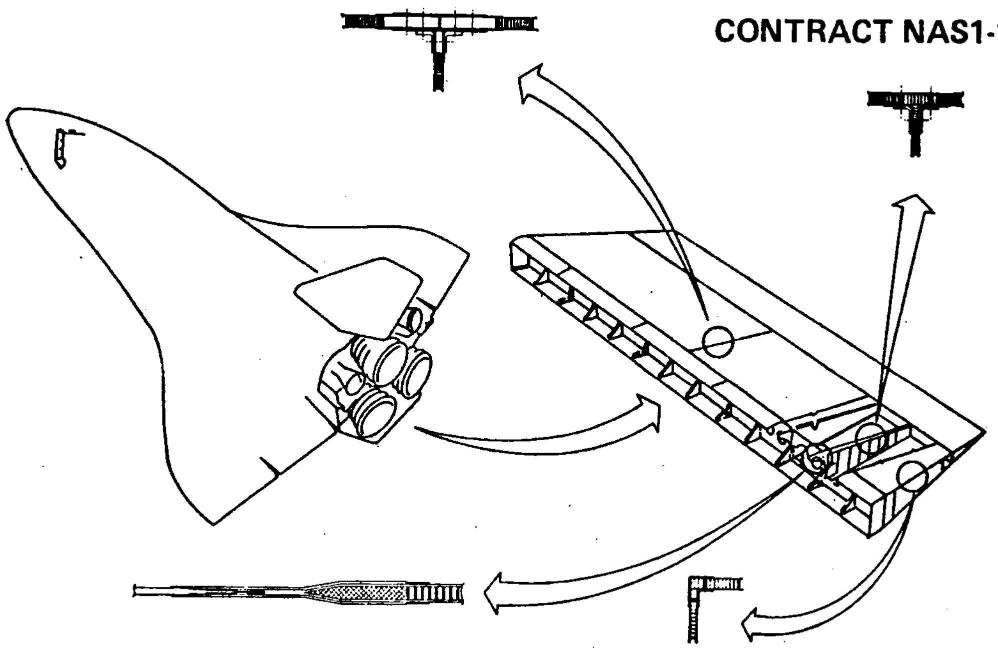
DESIGN, FABRICATION AND TEST OF GRAPHITE/POLYIMIDE COMPOSITE JOINTS AND ATTACHMENTS FOR ADVANCED AEROSPACE VEHICLES

QUARTERLY TECHNICAL PROGRESS REPORT NO. 1
COVERING THE PERIOD FROM
JANUARY 15, 1979 THROUGH MARCH 31, 1979

CONTRACT NAS1-15644



PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

APRIL 15, 1979

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ENGINEERING TECHNOLOGY
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N79-24066#

FOREWORD

This report summarizes the work performed by the Boeing Aerospace Company (BAC) under NASA Contract NAS1-15644 during the period January 15, 1979 through March 31, 1979.

This program is sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA/LaRC), Hampton, Virginia. Dr. Paul A. Cooper is the Technical Representative for NASA/LaRC.

Performance of this contract is by Engineering Technology personnel of BAC. Mr. J. L. Arnquist is the Program Manager and Mr. D. E. Skoumal is the Technical Leader.

The following Boeing personnel are principal contributors to the program during this reporting period: D. L. Barclay, Design; J. B. Cushman and J. J. Esposito, Analysis; G. D. Menke, Materials and Processes; R. E. Jones, Finite Element Analysis.

Prepared by D. E. Skoumal
Technical Leader

Approved by J. L. Arnquist
Program Manager

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SUMMARY

This document reports the design and analysis activities to date for a program to develop graphite/polyimide (Gr/PI) bolted and bonded joints. Status of the literature search of applicable experimental data and analysis is also presented.

Possible failure modes and the design loads for the four generic joint types are discussed. Preliminary sizing of a type 1 joint, bonded and bolted configurations is described, including assumptions regarding material properties and sizing methodology.

A general purpose finite element computer code is described that was formulated to analyze single and double lap joints, with and without tapered adherends, and with user-controlled variable element size arrangements.

An initial order of Celion 6000/PMR-15 prepreg has been received and characterized.

The program is essentially on schedule. A draft of the Test Plan for Task 2 has been submitted to NASA for approval and the test matrix for design allowables testing is being developed to support final sizing of the specific joint types.

SECTION 1.0

INTRODUCTION

This program is designed to extend the current epoxy-matrix composite technology in joint and attachment design to include polyimide matrix composites. This will provide the data necessary to build graphite/polyimide (Gr/PI) lightly loaded flight components for advanced space transportation systems and high speed aircraft. The objectives of this contract are two-fold: first, to identify and evaluate design concepts for specific joining applications of built-up attachments which could be used at rib-skin and spar-skin interfaces; second, to explore advanced concepts for joining simple composite-composite and composite-metallic structural elements, identify the fundamental parameters controlling the static strength characteristics of such joints, and compile data for design, manufacture, and test of efficient structural joints using the Gr/PI material system.

The major technical activities follow two paths concurrently. The TASK 1 effort is concerned with design and test of specific built-up attachments while the TASK 2 work evaluates standard and advanced bonded joint concepts.

The generic joint concepts to be developed under TASK 1 are shown in Figure 1-1. The total program is scheduled over a period of 27 months as shown in Figure 1-2.

In TASK 1.1, several concepts will be designed and analyzed for each bonded and each bolted attachment type. Concurrent with this task a series of design allowable and small specimen tests will be conducted under TASK 1.2. The analytical tesults of TASK 1.1 and the design data from TASK 1.2 will allow a selection of the most promising bonded and bolted concepts.

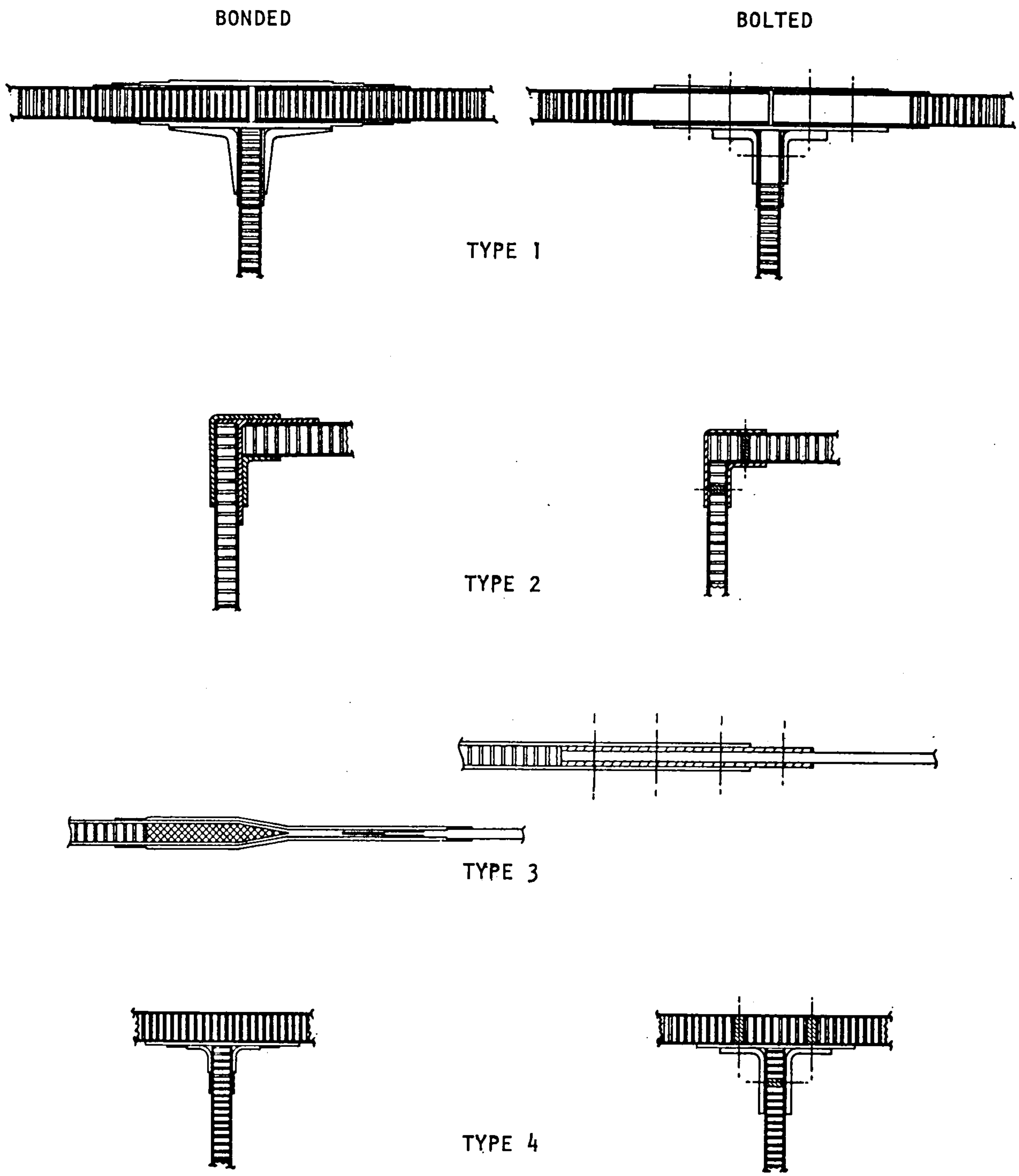


FIGURE 1-1. GENERIC JOINT CONCEPTS FOR 4 ATTACHMENT TYPES

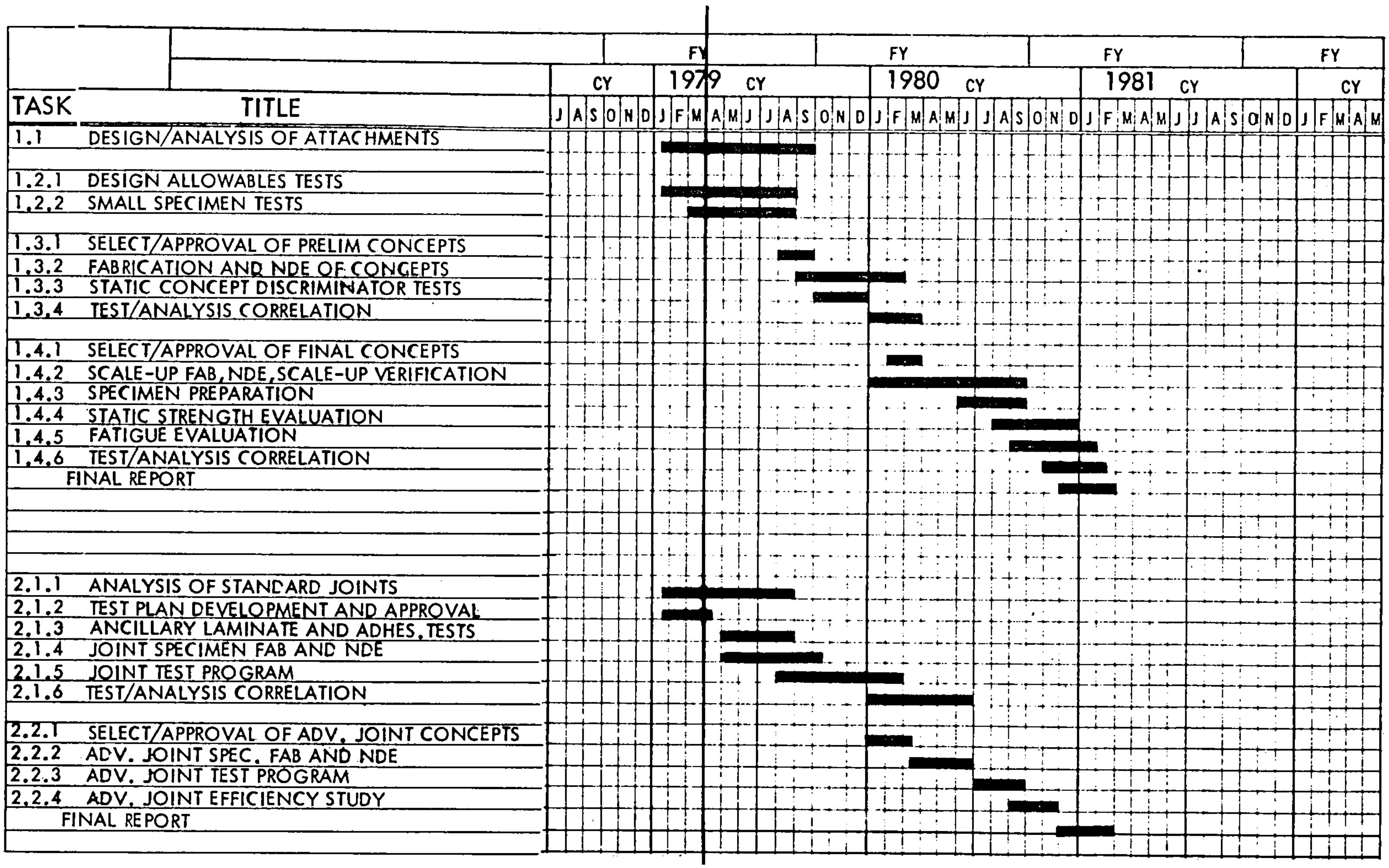


FIGURE 1-2. MASTER PROGRAM SCHEDULE

In TASK 1.3, the two most promising concepts for each joint type (16 concepts total) will be fabricated, tested, and evaluated. The evaluation will yield the preferred joint concepts and will be based on such criteria as weight efficiency, ease of fabrication, detail part count, inspectability, and projected fatigue behavior.

Finally, eight joint concepts (2 of each joint type) will be fabricated in TASK 1.4 on a scaled-up manufacturing basis to assure that reliable attachments can be fabricated for full-scale components. A series of static tests will be performed on specimens cut from the scaled-up attachments to verify the validity of the manufacturing process. Additional specimens will be thermally conditioned and tested in a series of static and fatigue tests. Test results will be compared with the analytical predictions to select final attachment concepts and design/analysis procedures.

The TASK 2 activity will establish a limited data base that will describe the influence of variations in basic design parameters on the static strength and failure modes of Gr/PI bonded composite joints over a 116K to 589K (-250°F to (600°F) temperature range. The primary objectives of this research are to provide data useful for evaluation of standard bonded joint concepts and design procedures, to provide the designer with increased confidence in the use of bonded high-performance composite structures, and to evaluate possible modifications to the standard joint concepts for improved efficiency.

To accomplish these objectives, activity under TASK 2.1 will consist of design, fabrication, and static test of several classes of composite-to-composite and composite-to-metallic bonded joints including single-and-double-lap joints, scarf joints, and step-lap joints. Test parameters will include lap length,

adhesive thickness, and adherend stiffness and stacking sequence at room and elevated temperatures. Toward the latter part of this program, under TASK 2.2, a selection will be made of advanced lap joint concepts which show promise of improving joint efficiency. Possible concepts are preformed adherends, mixed adhesive systems, and lap edge clamping. These concepts will be added to the static strength test program and the results compared with the results from the standard joint tests.

SECTION 2.0

TASK 1 ATTACHMENTS

2.1 TASK 1.1 Design and Analysis of Attachments

Investigation has commenced on the bonded and bolted concepts for each of the four attachment types shown in Figure 1-1. This section discusses the results achieved during this reporting period on the literature survey and the design and analysis of the joint concepts.

2.1.1 Literature Survey

A number of literature sources were searched using a wide range of key words to obtain information on graphite/polyimide composites pertinent to this contract. The search was not limited to graphite/polyimide composites since the available literature on this specific subject is limited and since design guide methods and parameters for other composites may be applicable to our joint designs. The following sources were searched:

SOURCE	TIME FRAME
o NASA	1978-1979
o NTIS	1964-1979
o CHEM ABSTRACTS	1972-1978
o ISMEC-MECH. ENGR.	1973-1977
o ENGINEERING INDEX	1970-1978
o SCISEARCH	1974-1978
o BOEING COMPANY DOCUMENTS	1974-1979
o BOEING TECHNICAL LIBRARY	1974-1979

Approximately 1500 articles and reports were identified as relevant and based on the abstracts about 200 were selected for further study.

A Defense Documentation Center (DDC) literature search will be conducted to obtain other references using a narrow range of key words to avoid encountering a large quantity of miscellaneous references.

2.1.2 Design/Analysis Flow Diagram

A flow diagram for conducting the design and analysis of the joint attachments for TASK 1.1 is shown in Figure 2-1. The diagram illustrates the interaction between design, analysis and test necessary to develop the joint designs.

2.1.3 Failure Mode Prediction

Possible failure modes for bonded and bolted joint configurations of the four attachment types were determined. Consideration was given to static strength evaluation at ambient and 589K (600°F) and fatigue evaluation at ambient and 589K (600°F). Tables 2-1 through 2-8 list the potential failure modes for each joint configuration. The fatigue failure mode was not listed in the tables because when it happens it will occur as one or more of the failure modes listed.

2.1.4 Preliminary Loads

Preliminary loads for the four attachment types have been determined for the load conditions defined in the contract Statement of Work (SOW). Loads for attachment types 1, 2 and 4 are shown in Tables 2-9 through 2-11. The load intensity for type 3 is 2.1 MN/m (12,000 lb/in) as specified in the SOW.

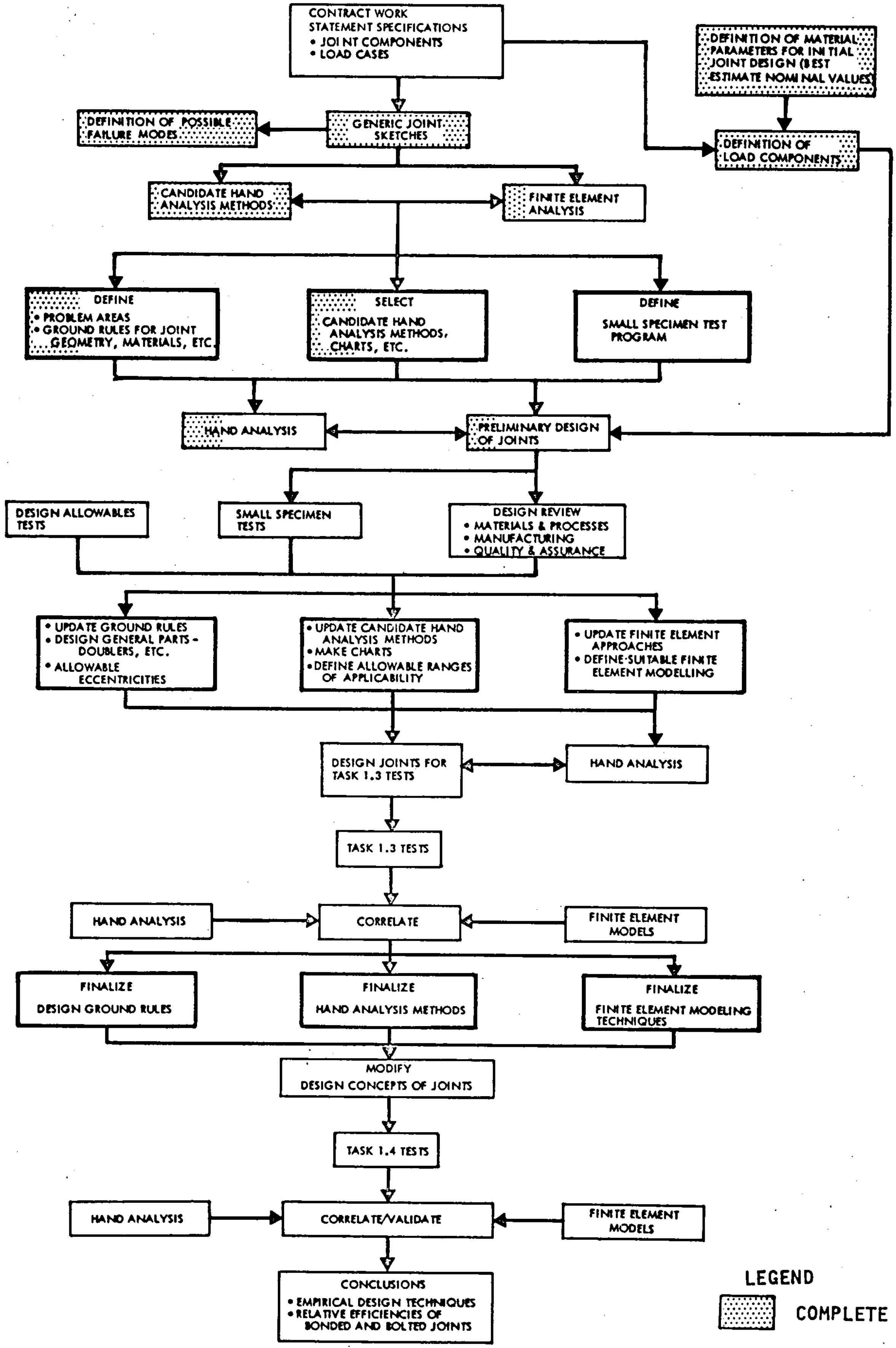
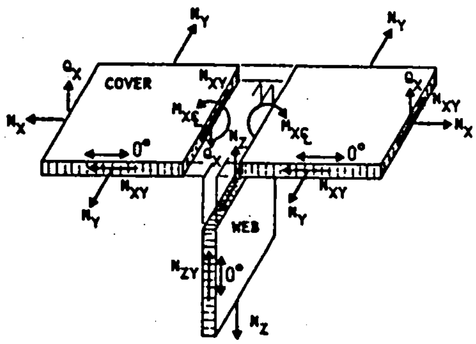
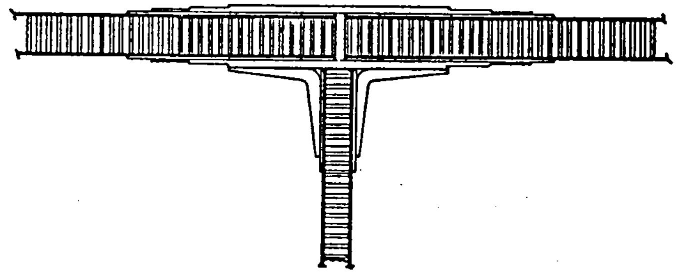


FIGURE 2-1. TASK 1 DESIGN/ANALYSIS FLOW DIAGRAM



NASA GUIDELINE CONCEPT



GENERIC JOINT

TABLE 2-1. POSSIBLE FAILURE MODES FOR BONDED ATTACHMENT TYPE NO. 1

At Cover Splice Plate

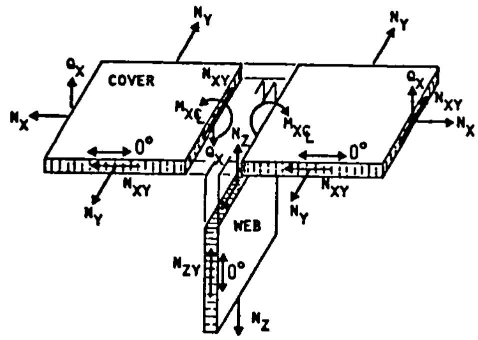
- o Face skin interlaminar tension
- o Face skin to core adhesive tension
- o Splice plate to face skin adhesive peel/shear
- o Splice plate to face skin adhesive shear
- o Splice plate - tension

At Attachment Angles to Cover

- o Face skin to core adhesive tension
- o Face skin interlaminar tension
- o Splice plate to face skin adhesive tension
- o Splice plate interlaminar tension
- o Angle to splice plate adhesive peel
- o Angle bending

At Attachment Angles to Web

- o Face skin interlaminar tension
- o Angle to face skin adhesive peel/shear



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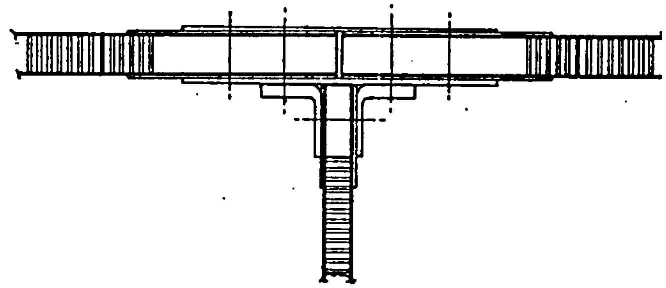


GENERIC JOINT

TABLE 2-2. POSSIBLE FAILURE MODES FOR BOLTED ATTACHMENT TYPE NO. 1

At Cover Doubler

- o Face skin interlaminar tension
- o Face skin to core adhesive tension
- o Doubler to face skin adhesive peel/shear

At Web Doubler

- o Face skin interlaminar tension
- o Face skin to core adhesive tension
- o Doubler to face skin adhesive peel/shear

At Cover Splice Plate

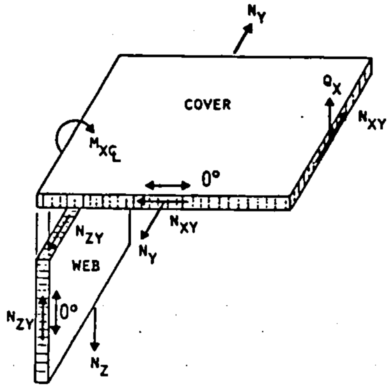
- o Splice plate/doubler/face skin - bearing/net tension/shearout

At Attachment Angles to Cover

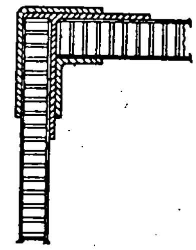
- o Core crushing
- o Splice plate/doubler/face skin - bearing/net tension/shearout
- o Angle bending
- o Bolt pull through

At Attachment Angles to Web

- o Core crushing
- o Angle/doubler/face skin - bending/net tension/shearout
- o Bolt pull through



NASA GUIDELINE CONCEPT



GENERIC JOINT

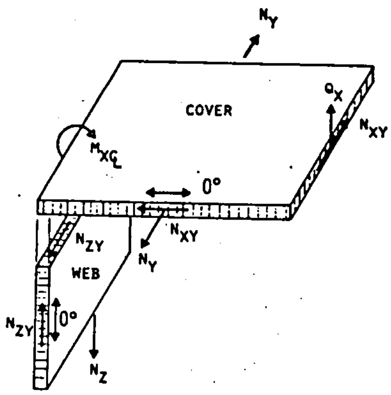
TABLE 2-3. POSSIBLE FAILURE MODES FOR BONDED ATTACHMENT TYPE NO. 2

At Corner Angles to Cover

- o Core tension
- o Face skin to core adhesive peel
- o Face skin interlaminar tension
- o Angle to face skin adhesive peel
- o Angle bending

At Corner Angles to Web

- o Core tension
- o Face skin to core adhesive peel
- o Face skin interlaminar tension
- o Angle to face skin adhesive peel



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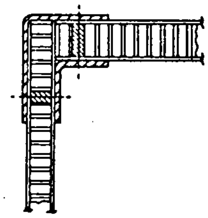


GENERIC JOINT

TABLE 2-4. POSSIBLE FAILURE MODES FOR BOLTED ATTACHMENT TYPE NO. 2

At Cover Doubler

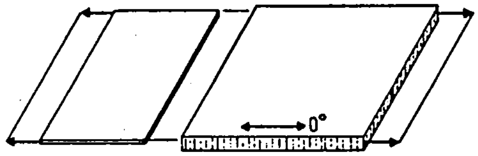
- o Face skin interlaminar tension
- o Face skin to cure adhesive tension
- o Doubler to face skin adhesive peel/shear

At Web Doubler

- o Face skin interlaminar tension
- o Face skin to core adhesive tension
- o Doubler to face skin adhesive peel/shear

At Attachment Angles to Cover/Web

- o Core crushing
- o Angle/doubler/face skin - bearing/net tension/shearout
- o Angle bending
- o Bolt pull through



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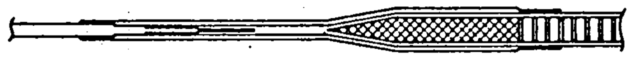


GENERIC JOINT

TABLE 2-5. POSSIBLE FAILURE MODES FOR BONDED ATTACHMENT TYPE NO. 3

At Doubler termination on panel

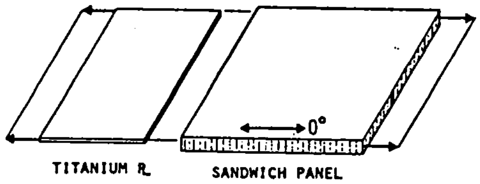
- o Face skin interlaminar tension
- o Doubler to face skin adhesive peel/shear

At Core Taper

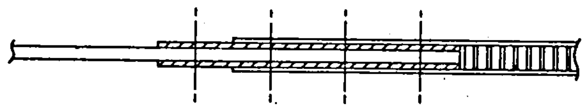
- o Core crushing
- o Core/adhesive tension

At Titanium Steps

- o Face skin/doubler interlaminar tension
- o Face skin/doubler to titanium adhesive peel
- o Tension failure of titanium steps



NASA GUIDELINE CONCEPT



GENERIC JOINT

TABLE 2-6. POSSIBLE FAILURE MODES FOR BOLTED ATTACHMENT TYPE NO. 3

At Doubler Termination on Panel

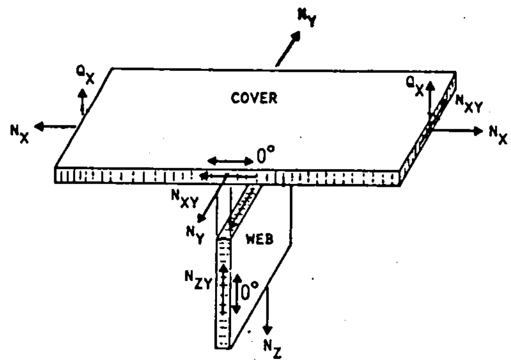
- o Face skin interlaminar tension
- o Doubler to face skin adhesive peel/shear

At Core Taper

- o Core crushing
- o Core/adhesive tension

At Titanium Steps

- o Face skins/doublers/titanium - bearing/net tension/shearout
- o Fastener shear



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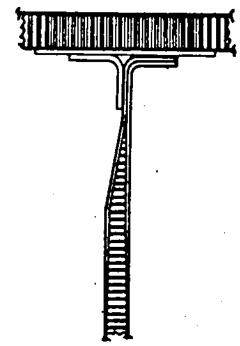


GENERIC JOINT

TABLE 2-7. POSSIBLE FAILURE MODES FOR BONDED ATTACHMENT TYPE NO. 4

At Cover Doubler

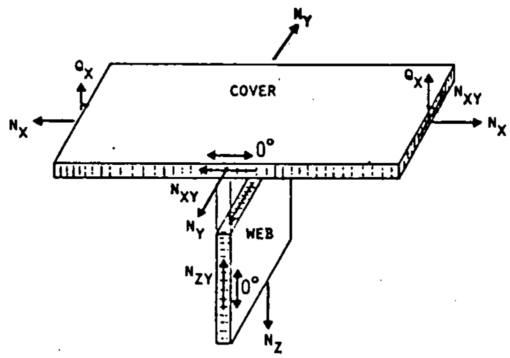
- Face skin interlaminar tension
- Face skin to core adhesive tension
- Doubler to face skin adhesive peel/shear

At Attachment Angles to Cover

- Face skin to core adhesive tension
- Face skin interlaminar tension
- Doubler to face skin adhesive tension
- Doubler interlaminar tension
- Angle to doubler adhesive peel
- Angle bending

At Attachment Angles to Web

- Face skin interlaminar tension
- Angle to face skin adhesive peel/shear



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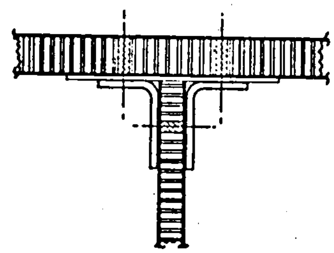


GENERIC JOINT

TABLE 2-8. POSSIBLE FAILURE MODES FOR BOLTED ATTACHMENT TYPE NO. 4

At Cover Doubler

- o Face skin interlaminar tension
- o Face skin to core adhesive tension
- o Doubler to face skin adhesive peel/shear

At Attachment Angles to Cover

- o Core crushing
- o Face skin net tension at bolt holes
- o Doubler/face skin/attachment angle - shearout
- o Angle bending
- o Bolt pull through

At Attachment Angles to Web

- o Core crushing
- o Angle/doubler/face skin -bearing/net tension/shearout

TABLE 2-9. PRELIMINARY LOADS FOR TYPE 1 JOINTS

CASE	LOAD CONDITION	RATIO	VALUE kN/m (lb/in)
1	N_x	1	442.3 (2526)
	N_{xy}	0.03 N_x	13.3 (76)
	N_y	0.15 N_x	66.4 (379)
	N_{zy}	0.10 N_x	44.3 (253)
	N_z	0.02 N_x	8.9 (51)
	$M_{x\text{℄}}$	(0.10 in) N_x	1.1* (253*)
	Q_x	0.01 N_x	4.4 (25.3)
2	N_x	1	239.6 (1368)
	N_{xy}	0.03 N_x	3.2 (41)
	N_y	0.15 N_x	35.9 (205)
	N_{zy}	0.10 N_x	24.0 (137)
	N_z	0.12 N_x	28.7 (164)
	$M_{x\text{℄}}$	(0.50 in) N_x	3.0* (684*)
	Q_x	0.06 N_x	14.4 (82)

LAYUP: COVER $(0/90/\pm45)_s$ WEB $(0/\pm45)_s$

*kN·m/m (lb-in/in)

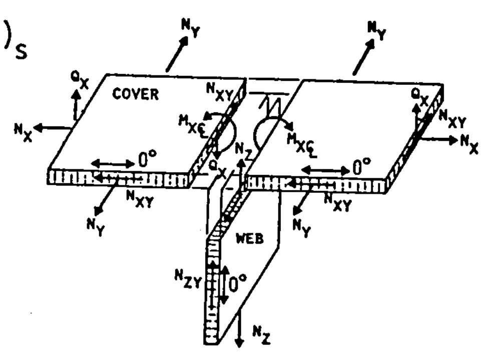


TABLE 2-10. PRELIMINARY LOADS FOR TYPE 2 JOINTS

CASE	LOAD CONDITION	RATIO	VALUE kN/m (lb/in)
1	N_x	0	
	N_y	1	560.4 (3200)
	N_{xy}	0.10 N_y	56.0 (320)
	N_{zy}	0.10 N_y	56.0 (320)
	N_z	0.02 N_y	11.2 (64)
	$N_{x\mathbb{C}}$	(0.01 in)N_y	0.1* (32*)
	Q_x	0.02 N_y	11.2 (64)
2	N_x	0	
	N_y	0.40 N_{y1}	224.1 (1280)
	N_{xy}	0.10 N_y	22.4 (128)
	N_{zy}	0.10 N_y	22.4 (128)
	N_z	0.10 N_y	22.4 (128)
	$M_{x\mathbb{C}}$	(0.05 in) N_y	0.3* (64*)
	Q_x	0.10 N_y	22.4 (128)

LAYUP: COVER $(0/90/\pm45)_s$ WEB$(0/\pm45)_s$

*kN·m/m (lb-in/in)

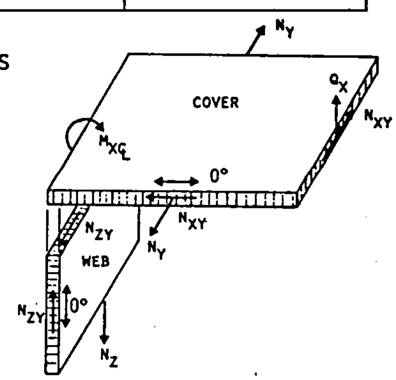
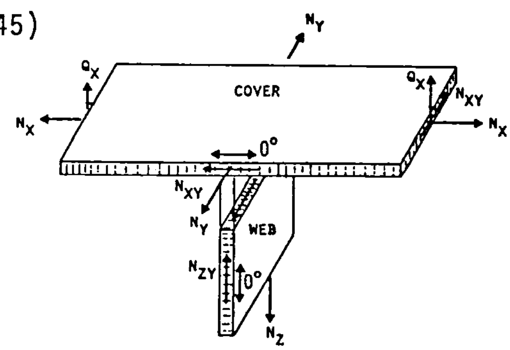


TABLE 2-11. PRELIMINARY LOADS FOR TYPE 4 JOINTS

CASE	LOAD CONDITION	RATIO	VALUE kN/m (lb/in)
1	N_x	1	200.2 (1143)
	N_{xy}	0.03 N_x	6.0 (34)
	N_y	0.15 N_x	30.1 (172)
	N_{zy}	0.10 N_x	20.0 (114)
	N_z	0.02 N_x	5.0 (28)
	$M_{x\mathbb{C}_L}$	(0.10 in) N_x	0.5* (114*)
	Q_x	0.01 N_x	2.0 (11.4)
2	N_x	1	93.3 (533)
	N_{xy}	0.03 N_x	2.8 (16)
	N_y	0.15 N_x	14.0 (80)
	N_{zy}	0.10 N_x	9.3 (53.3)
	N_z	0.12 N_x	11.2 (64)
	$M_{x\mathbb{C}_L}$	(0.50 in) N_x	1.2* (266.5*)
	Q_x	0.06 N_x	5.6 (32)

LAYUP: COVER (0/90/±45) WEB (0/±45)

*kN·m/m (lb-in/in)

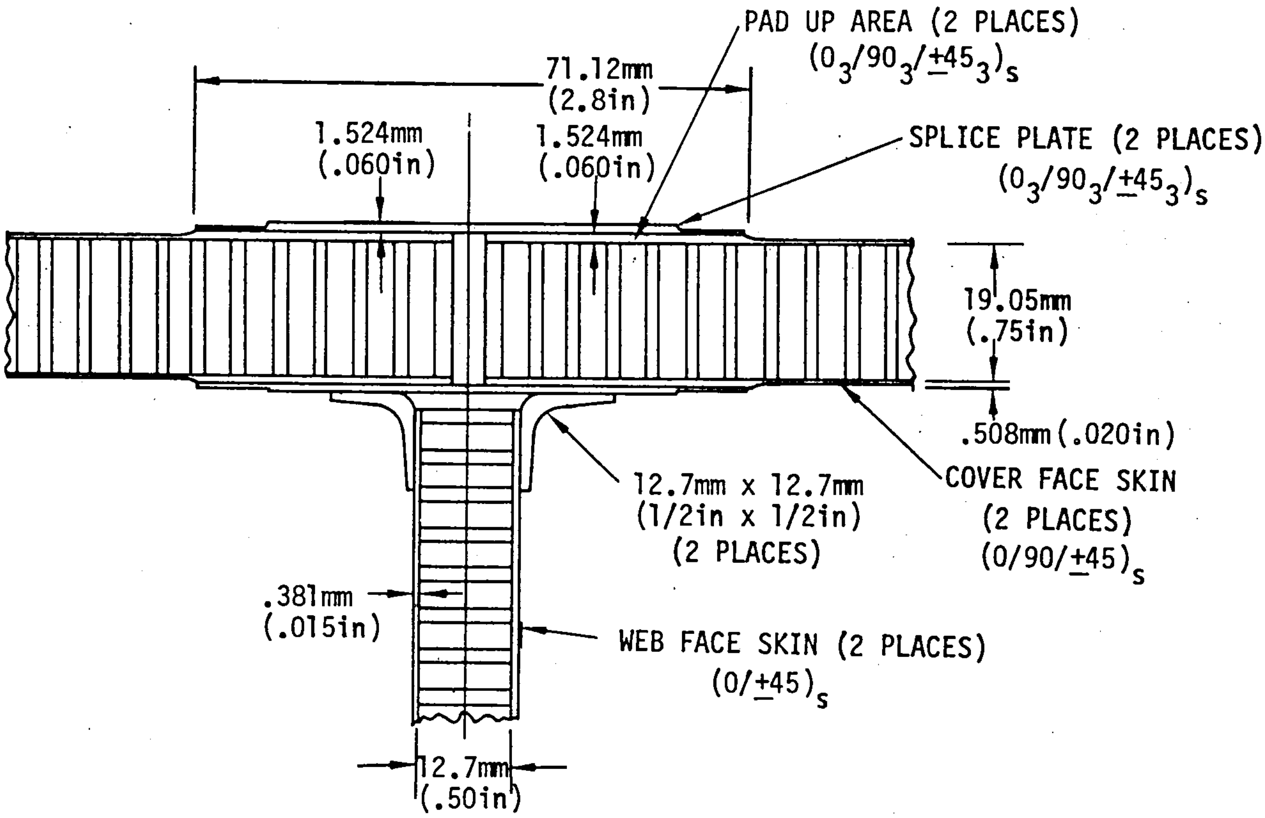


Loads for type 1, 2 and 4 attachments are based on failing the cover face sheets outside the joint. They are estimates based on the laminate layups and corresponding material properties. The layups are specified in the SOW; however, material properties for the actual Gr/PI laminates will be determined under TASK 1.2 Design Allowables. Preliminary loads therefore are based on using representative material properties for Gr/PI laminates from Reference 1. For the specified layup an ultimate tensile value (F_{Tu}) of 551.6 MN/m^2 (80,000 psi) was used. Ultimate loads for type 1 and 4 attachments are determined by net tension in the cover face sheets due to the axial load N_x and the moment $M_{x\mathbb{C}}$. Type 2 attachment ultimate loads are determined by net tension in the cover face sheets due to the load N_y.

The loads shown in Tables 2-9 through 2-11 are preliminary. Values will change as Gr/PI material properties become available and as the joint designs are evolved. Configuration of the joint detail design will affect how the moment $M_{x\mathbb{C}}$ is reacted in the face sheets and may require an increase in N_x to initiate a failure outside the joint.

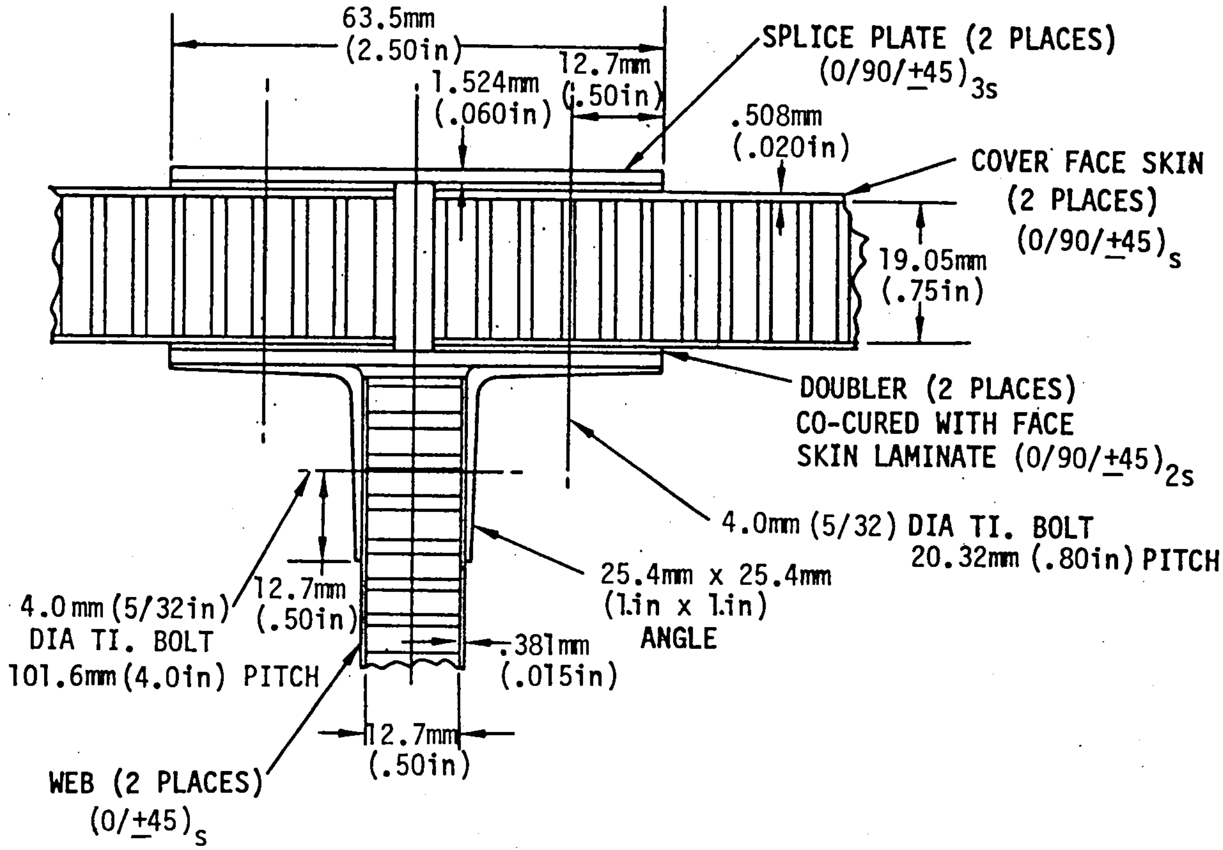
2.1.5 Preliminary Design of Joints

Preliminary sizing of bonded and bolted type 1 joints, using the loads defined in Section 2.1.4, has been completed. Joint configurations are shown in Figures 2-2 and 2-3. Designs presented are for room temperature and static load conditions. Requirements for 589K (600°F) operation and fatigue will be identified later. By using room temperature designs as a baseline, design penalties for 589K (600°F) operation and fatigue can be easily identified. Analysis procedures used to arrive at these joint designs are presented below.



- N_X IS PREDOMINATE DESIGN LOAD
- UNCERTAINITIES
  - LAP LENGTH
  - STIFFNESS BALANCE
  - THERMAL BALANCE
  - MATERIAL PROPERTIES

FIGURE 2-2. PRELIMINARY DESIGN FOR BONDED ATTACHMENT TYPE 1



- BASED ON BEARING CRITICAL DESIGN
- N_X IS PREDOMINATE DESIGN LOAD
- CONTINUOUS ATTACHMENT ANGLE MAY NOT BE REQUIRED
- UNCERTAINTIES
  - STRESS CONCENTRATION AT END OF DOUBLER
  - STIFFNESS BALANCE
  - THERMAL BALANCE
  - MATERIAL PROPERTIES

FIGURE 2-3. PRELIMINARY DESIGN FOR BOLTED ATTACHMENT TYPE 1

Bonded Type 1 Joint

Loads for type 1 joints include a moment at the joint centerline. This moment is reacted as a couple in the cover face sheets resulting in an unsymmetrical load in the double lap joint. There is a higher line load at the bottom than at the top since the couple adds and subtracts, respectively, to the applied tension load (N_x). For this reason the bottom of the cover was analyzed as a single lap joint to estimate the required bonded lap length. This is conservative since moments and tension loads introduced by load eccentricities in a free single lap joint are minimized in our case by the fixity provided by the honeycomb sandwich.

Adhesive properties are the most critical for determining required lap lengths. Specific single lap design curves are not available for Gr/PI adherends with LARC-13 adhesive. Reference 2 was reviewed to select a single lap design curve for composite adherends with an adhesive closely matching LARC-13. Bloomingdale HT424 adhesive was selected as most closely matching LARC-13. HT424 has a shear modulus of approximately 2.1 GN/m^2 (300,000 psi) and an ultimate shear stress of 24.8 kN/m^2 (3600 psi). Both HT424 and LARC-13 are considered high modulus/brittle adhesives. Figure 1.3.1-15 from Reference 2 was used for preliminary sizing of the bonded joint. Although the load at the top of the cover is lower than the bottom, the bonded lap length was made the same as the bottom to provide symmetrical joint stiffness.

The optimum joint design requires both stiffness and thermal balance. Since we are bonding identical laminate materials, thermal balance (except for the adhesive) is achieved automatically. Stiffness balance is achieved

by matching the Et (modulus times thickness) of the adherends. There is an inherent stiffness mismatch where the web attach angle is bonded to the lower cover splice plate. To compensate for this the splice plate extends past the attach angle. This allows the major load transfer, which occurs at the end of the adherend, to occur in an area that still has stiffness balance.

Loads on the web attach angle are quite small. The theoretical bonded lap length required is less than 2.54 mm (0.10 in). From an assembly standpoint this is probably too small to be practical. Angles every 152.4 mm (6 in) with 12.7 mm (0.5 in) legs are recommended. The corner of the angle must be reinforced to take the bending loads.

Bolted Type 1 Joint

The bolted type 1 joint was sized by analyzing for the three basic failure modes identified in Section 1.3.2.1 of Reference 2. These are bearing, shearout and net tension. Shear and bearing failure of the fastener and bolt pull-through were considered not to be critical.

Minimum weight dictated a titanium fastener where the minimum size available is 4.166 mm (0.164 in) diameter. This size is more than adequate for the applied shear load (maximum load occurs at the bottom of the cover as discussed previously). A bolt spacing of 5D, edge margins of 2.75D and a minimum diameter to thickness ratio (D/t) of 1.0 were used as recommended in Reference 3.

Material properties for bearing (F_{BRU}), net tension (F_{TUnet}) and shearout (f_{SO}) were not available for Gr/PI laminates; therefore, corresponding

values for graphite/epoxy from Reference 3 were used for preliminary sizing of the joint. Shearout was analyzed by using a design curve that gave equivalent bearing stress as a function of edge margin. The equations used are as follows:

Allowable Bearing Load $P_{BRG} = Dt\ F_{BRU}$

Allowable Tension Load $P_{TENS} = 2(\frac{S}{D} - 0.5)\ Dt\ F_{TUnet}$

where:

D	=	Bolt Dia.
t	=	Material thickness
S	=	0.5 Bolt spacing
F_{BRU}	=	Allowable ultimate bearing stress
F_{TUnet}	=	Allowable net tension stress.

Analysis results show that the doubler and splice plate thickness are controlled by F_{BRU} which means the joint is bearing critical. This is desirable since it does not precipitate a catastrophic failure.

Loads in the web attach angle are quite low and can be easily accommodated by intermittent angles. Angles are spaced so they pick up existing bolts in the cover. The angles must be reinforced in the corners to take the bending loads.

2.1.6 Analysis Methods

From the standpoint of a designer, analysis of bonded joints should be as simple as possible to enable rapid and easy sizing. For single and double lap joints this is most easily accomplished if there are specific design curves for the laminate, adhesive and joint configuration being considered.

These curves should show apparent ultimate shear stress (F_a^{SU}) versus bonded lap length (la). The joint allowable load (N_{xcr}) is given by

$$N_{xcr} = F_a^{SU} \, la \quad \text{per mm (in) of width}$$

This is the approach being used for preliminary sizing of bonded joints. Existing design curves based on adhesive and laminate properties as close as possible to ours are being used to determine preliminary lap lengths. Joints will be derated to account for thermal and stiffness mismatch as required using the non-dimensionalized derating factors presented by L. J. Hart-Smith (Reference 4).

Critical analyses of the type 3 joint show a simple double lap bonded joint will not be adequate. Preliminary sizing of a symmetrical step lapped joint will be based on procedures in Section 1.3.1.2.1.6 of Reference 1.

For bolted joints sizing is based on analyzing for the three basic failure modes identified in Section 1.3.2.1 of Reference 2. These are bearing, shearout, and net tension. Shear and bearing failure of the fasteners and bolt pull through must also be considered. Since basic material properties for Gr/PI are not yet available preliminary sizing is based on existing graphite/epoxy properties from Reference 3. Room temperature values used are:

Bearing Ultimate F_{BRU} = 966.3 MN/m^2 (140,000 psi)

for e/D = 2.75

Net Tension Ultimate F_{TUnet} = 372.3 MN/m^2 (54,000 psi)

Minimum bolt spacing of 5D, row spacing of 4D, edge margin of 2.75D and diameter to thickness ratio (D/t) of greater than 1.0 as recommended in Reference 3 are used as preliminary guidelines to design the joints.

If there are 3 or more rows of bolts taking the load, load peaking on the outermost bolts is considered.

For bolted composite materials reinforced with metal shims, the analysis equations presented in Section 1.3.2.5.2 of Reference 2 will be used.

2.2 MATERIAL AND SMALL COMPONENT CHARACTERIZATION

2.2.1 Materials

As required by the contract, NASA specified the graphite fiber, polyimide matrix, and adhesive systems to be used. Celion fiber in either 6000 or 3000 filament form was specified. PMR-15 resin was chosen as the matrix resin, with the processing to be according to the procedures Boeing developed under NASA Contract NAS1-15009. LARC-13/Amide-Imide modified adhesive will be used, with the base LARC-13 solution being supplied by NASA/LaRC.

The Process Control and Verification task described in the original statement of work (i.e., in the RFP) was not included as a task in Contract NAS1-15644 since (1) Boeing was already conducting most of the required laminate process control evaluation as part of the Task J ("Variability") add-on to Contract NAS1-15009 and (2) the remaining tests would be conducted as part of the 1979 Advanced Composites IR&D program. Relevant results of these programs to date:

- o 13.62 kg (30 lbs) of Celion 6000/PMR-15 prepreg was ordered in January to the requirements of Boeing document D180-20545-4,

"Graphite/PMR-15 Prepreg Material Specification". This preliminary specification was prepared as part of Contract NAS1-15009 and is a part of the final report. Prepreg physical and chemical properties were typical of the product U.S. Polymeric had supplied for the NAS1-15009 contract, and the process control panel, fabricated per D180-20545-5 (Process Specification for Graphite/PMR-15 Prepreg), met all C-scan requirements.

o The initial results of the Variability add-on to Contract NAS1-15009 were so encouraging that Boeing requested a change to PMR-15 resin processed according to the results of the variability program. Dr. John Davis, CASTS Program Manager, reviewed the data documenting the improved processability and uniformity of properties and approved the change.

o In anticipation of the change to more tightly controlled prepreg, additional evaluation of the original prepreg order was discontinued. A replacement order was placed on March 9, with an additional 22.7 kg (50 lbs) ordered at the same time. The additional prepreg will be used to fabricate specimens in Tasks 1.2.2 and 2.1.3. Prepreg delivery is scheduled to be in the first or second week of April. Prepreg evaluation and panel fabrication for Task 1.2.1 Design Allowables specimens will be conducted simultaneously in order to minimize schedule slip caused by the tightening of the controls on the PMR-15 resin and on prepregging operations.

SECTION 3.0

TASK 2 BONDED JOINTS

3.1 TASK 2.1.1 Analysis of Standard Joint Concepts (Boeing IR&D)

3.1.1 Analysis Methods

Joint analyses under this task will be performed using Boeing's BOPACE program (Boeing Plastic Analysis Capability for Engines). This program handles geometric nonlinearities, plasticity, and creep. Finite element models are generated using a higher level, FORTRAN-based preprocessing language (BOEING's SAIL: Structural Analysis Input Language) which creates BOPACE input data. The present preprocessing code is capable of generating single and double lap joints, with and without tapered adherends, and with user-controlled variable element size arrangements. Different lamina can be stacked arbitrarily in the adherends. This code is currently being extended to handle more general arrangements, including scarfed, stepped-lap, and doubler-reinforced joints. The BOPACE computed results are passed to an interactive graphics facility, where joint deformations can be quickly studied in detail.

Deformations of various joint types are shown in Figures 3-1 through 3-4. Linear and elastic checkout cases have been computed using metal adherends. Figures 3-1 through 3-4 illustrates typical results for single lap joints. Analyses will be extended to include nonlinear, inelastic examples and other joint geometries, as noted above. In addition, near-future checkout cases will be run using typical graphite/epoxy properties, including best-estimate cross-ply stiffnesses. The model can be easily used with graphite/polyimide

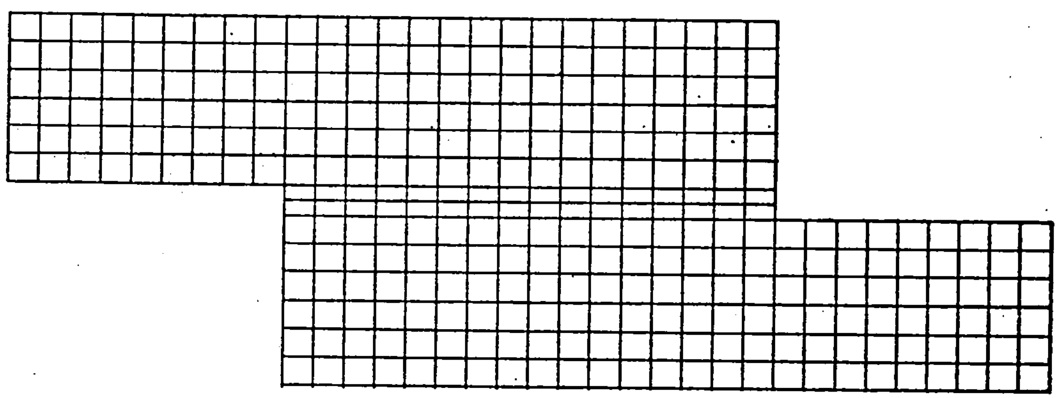


FIGURE 3-1. UNDEFORMED STRUCTURE - UNIFORM GRID MODEL

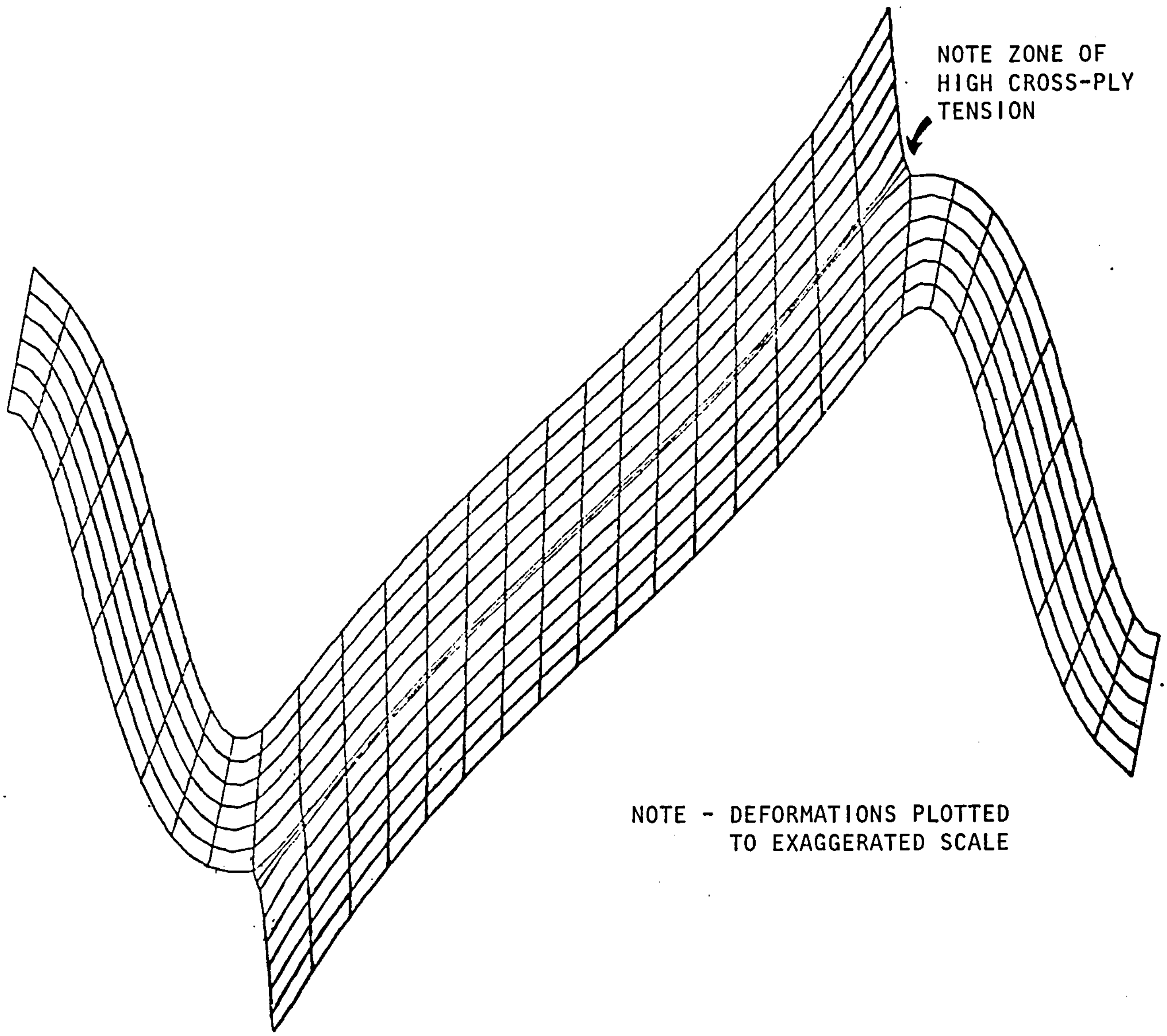


FIGURE 3-2. DEFORMED STRUCTURE - UNIFORM GRID MODEL

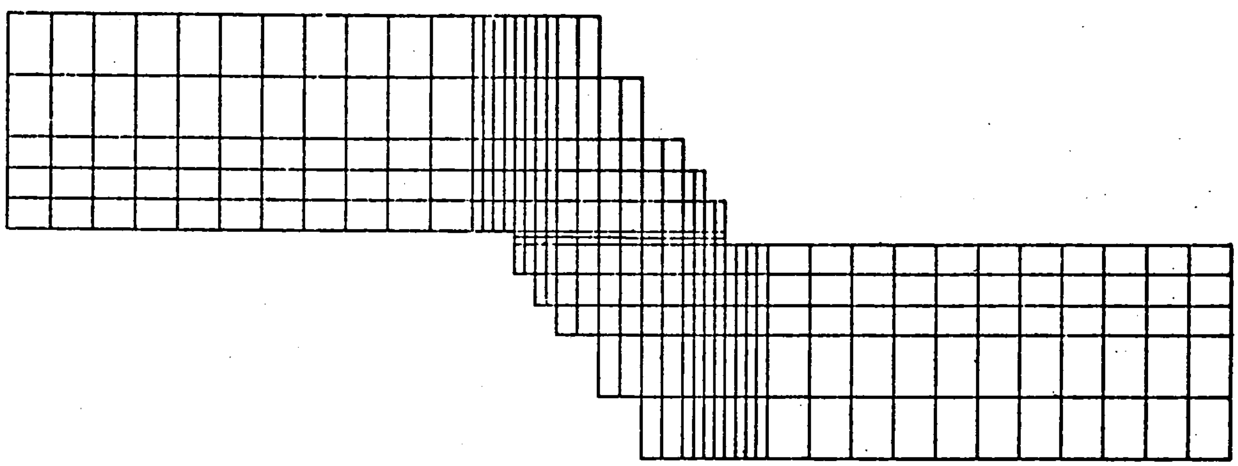


FIGURE 3-3. TAPERED SINGLE LAP UNDEFORMED STRUCTURE - VARIABLE GRID MODEL

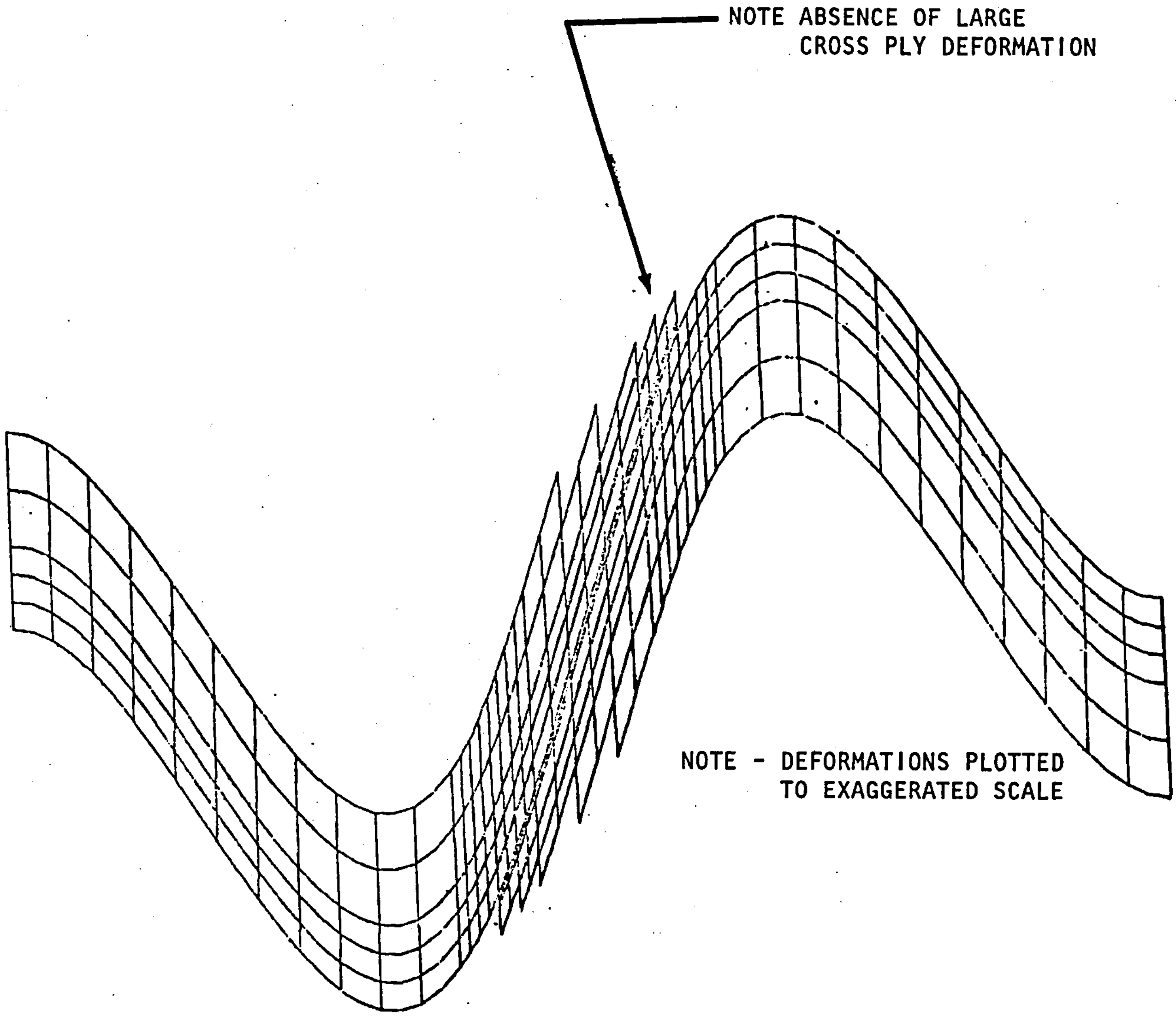


FIGURE 3-4. DEFORMED STRUCTURE - VARIABLE GRID MODEL

properties, as these data become available in the future. It is expected that smaller element sizes may be needed for the polyimide analysis, but this can easily be handled by means of the input data processing code.

SECTION 4.0

PROGRAM ANALYSIS

This section of the quarterly report will assess the key results of the work performed during the reporting period, draw conclusions based on these results, and make recommendations when applicable.

REFERENCES

1. C. H. Sheppard, J. T. Hoggatt, and W. A. Symonds, "Development and Demonstration of Manufacturing Processes for Fabricating Graphite/PMR-15 Polyimide Structural Elements", Boeing Document D180-20545-2, April 1979, Contract NAS1-15009.

2. Air Force "Advanced Composite Design Guide", Vol. 1, Sept. 1976, 3rd Edition (2nd Rev.).

3. Boeing "Advanced Composites Design Handbook", D6-44714, Rev. 7-17-78.

4. L. J. Hart-Smith, "Adhesive-Bonded Double-Lap Joints", NASA CR-112235, January 1973, Contract NAS1-11234.